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B Physics at the Fermilab Tevatron After the Year 2000

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Abstract

The requirements for second-generation B experiments at hadron colliders are discussed. The prospects for mounting such an experiment at the Fermilab Tevatron Collider are reviewed. Early results from a design study which is intended to produce an optimum detector for the Tevatron are presented.

1. Introduction

B-physics experiments which have hopes of achieving enough sensitivity to observe and study CP violation and the related topic of B_s mixing are being constructed at several locations: at new asymmetric energy e^+e^- colliders at SLAC [1] and KEK [2]; at the existing symmetric energy e^+e^- collider [3], CESR, at Cornell; at a novel fixed target experiment using the proton beam halo at HERA, the HERA-B experiment [4]; and in $\bar{p}p$ experiments using upgraded versions of the two "general purpose" detectors, CDF [5] and D0 [6], at the Fermilab Tevatron. This may truly be characterized as a "world-wide" effort.

In this paper, we explore the prospects for a "second generation" B-physics experiment at the Fermilab Tevatron after the year 2000. We begin by reviewing the capabilities expected in the "first generation" experiments mentioned above; we then state what we believe are the requirements for a "second generation" experiment; we describe the evolution of the Fermilab Collider into the early years of the next millenium - including its luminosity and bunch spacing and its scientific program options; next we describe the goals and activities of the B-Physics Design group at Fermilab; we present some early results on the sensitivity for $\sin 2\alpha$ obtained from simulation of both central and forward detectors; and finally we describe the future activities and goals of the design effort.

2. Prospects for the first generation experiments; requirements for second generation experiments

B physics probes a significant fraction of the CKM matrix and offers a large variety of possible measurements, including B lifetimes, charmless B decays, B^0–$\bar{B}^0$ mixing, CP-violating asymmetries, B_s–$\bar{B}_s$ mixing and rare (FCNC) decays. B-physics tests the Standard Model explanation of CP violation. While people tend to focus on a few asymmetries which have relatively clean theoretical explanations and experimental signatures, there is a rich variety of possible asymmetries including indirect CP violation in the neutral mesons and direct CP violation in mesons and baryons, charged and uncharged. Most importantly, we should not lose sight of the fact that we are hoping to observe new physics which is not consistent with the Standard Model.

The first round of experiments that hope to achieve sensitivity at the expected level of CP violation will begin in the next few years and accumulate significant data by the year 2000. As an indication of what these experiments can accomplish, we show in Table 1 the sensitivity for $\sin 2\beta$ and $\sin 2\alpha$ predicted for the BaBar experiment at SLAC [1]. The BELLE experiment at KEK has similar sensitivity The HERA-B experiment expects to achieve a sensitivity $\delta(\sin 2\beta)$ of 0.19 per year of running, assuming a production cross section of 6 nb. CDF and D0, running at the Tevatron after the Main Injector Upgrade, hope to achieve comparable sensitivity.

While these experiments have an excellent opportunity to observe CP violation and begin its study, many of us believe that these experiments will not answer all of the relevant questions. The e^+e^- machines will simply run out of produced B's, unless some major new breakthroughs in

Table 1
Predicted sensitivity for CKM angles for BaBar per Snowmass year

Mode	Tagged events	$\delta(\sin 2\phi)$
ψK_s	1106	0.098
ψK^*	307	0.19
$\pi^-\pi^-$	346	0.20
$\pi^-\pi^-\pi^0$	1162	0.11

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machine luminosity can be achieved. The experiments, as planned, are already highly efficient. The hadron colliders, on the other hand, are increasing their luminosity and the first generation of detectors are limited in many ways. Significant improvements in sensitivity can therefore be obtained. Hadron colliders have large cross sections for the full range of particles containing b-quarks: B^0, $B^{\pm}$, B_s, B_c, and Λ_b's. They therefore provide an excellent opportunity for a broad range of very high sensitivity studies of B-physics, including mixing and CP violation. Many of us believe that there should be a second generation of CP violation experiments at hadron colliders whose goals are to greatly exceed the capabilities of the first generation experiments.

We are considering the prospects for such an experiment at the Fermilab Tevatron. The requirements for such an experiment are:

- It must constitute a significant improvement in sensitivity and scope over the first generation experiments; and

- It must be timely and competitive with respect to any follow-on experiments to first-generation efforts and with respect to the proposed LHC-B experiment at the LHC [7].

3. Evolution of the Fermilab Tevatron Collider and its program

Table 2 shows the evolution of the luminosity and bunch spacing of the Fermilab Collider beginning in 1993 and projected to the year 2004 and beyond. While the luminosity goals are now set, the bunch spacing for RUN III is still being evaluated by the machine experts who hope to be able to reduce it further. While there is optimism that some reduction can be achieved, there are significant problems still to be solved.

The machine will continue to run at a center of mass energy of 2 TeV during this period.

It is reasonably certain that B experiments will not be able to use the full luminosity of the Tevatron in RUN III. Because these experiments need precision vertex reconstruction, tracking elements need to be placed very close to the interaction region. These elements then must deal with high occupancy and with severe radiation environments. Equally important, the experiments must trigger against very large backgrounds of uninteresting events and require time to make the selection at the appropriate level. Most of us believe that these second-generation B-experiments will not be able to run much above 1 or 2×10^{32} without limiting their scope. Since the ability of the detectors and their triggers to deal with multiple interactions per crossing is not well understood but believed to be quite limited, bunch spacing is an important consideration.

Table 2
Luminosity evolution of the Tevatron Collider

Time period	Luminosity $(cm^2\ s)^{-1}$	Bunch spacing (ns)
RUN I (1992–1996)	2.5×10^{31}	3500
RUN II (1998–2002)	2.0×10^{32}	396 — 132
RUN III (2004+)	1.0×10^{33}	132 (or less)

Run I will end in the late winter of 1996. By the end of 2002, the so-called RUN II will be over. Collider RUN III is expected to begin around the year 2004.

Fermilab expects to continue to have only two interaction regions capable of supporting large detectors. One of these regions will almost certainly have a detector optimized for high-P_t or high-mass physics. It is not clear whether this will be built on the foundation of one of the two existing detectors or whether it will be essentially a completely new detector.

The options for the other collision region are:
- A second high-P_t detector;
- A detector dedicated to and optimized for B-physics:
  (i) built on the foundation of one of the existing detectors; or
  (ii) a completely new detector;
- Some other detector addressing other physics – such as a full acceptance detector.

Recent recommendations by the Fermilab Program Advisory Committee seem to favor a dedicated B detector of an as yet unspecified kind. About 18 months ago, Fermilab called for expressions of interest for experiments for Collider Run III. A group of physicists, of which I am a member, submitted an expression of interest (so-called EOI-2) [8] to conduct a detailed design study for a dedicated B detector at the Tevatron. One year ago, the lab set up an organization to provide resources to develop a simulation package to aid in the design of the detector and to provide a tool for the lab management to use to make independent evaluations of various proposed experiments at Fermilab and to compare them with experiments that will be running in the same time frame. The software simulation package, known as MCFAST [9], is now well along in its development. The remainder of this paper describes some of the results which have been obtained from the investigations associated with the study by the EOI-2 group using MCFAST.

4. Recent simulation results

Consideration of future B-physics experiments at Fermilab must start from the recognition that the two existing detectors, CDF and D0, do have significant capabilities for studying B physics and have hopes of improving those capabilities in future upgrades. Any detector that would displace one of them must demonstrate significantly higher sensitivity. In designing a detector for B physics at a hadron collider, one is faced with the fact that the events are distributed over a very wide range in rapidity and transverse momentum and the characteristics of the particles which must be detected vary dramatically as a function of rapidity and P_t.

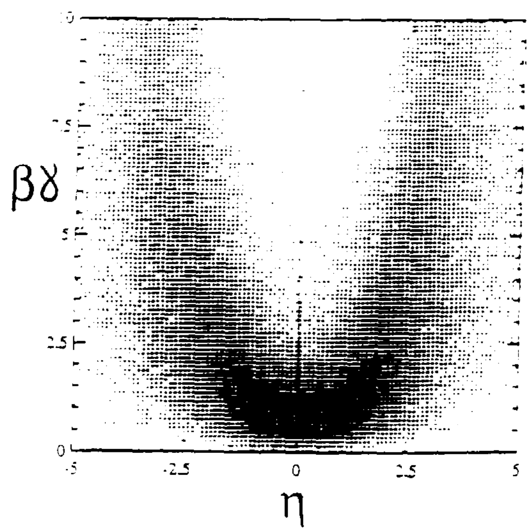

Fig. 1. $\beta \times \gamma$ for B-meson vs η of B-meson.

Fig. 1 shows the $\beta \times \gamma$ of the B-mesons as a function of rapidity. It is clear that the momentum of the B, the momenta of the decay products, the separation of the production and B-decay vertices, and the importance of multiple scattering on vertexing and tracking are all very strong functions of the kinematics. Since B production is rather spread out, it is possible to define a variety of detectors that have good acceptance to a reasonable fraction of the B production – some which emphasize acceptance in the forward direction and some which emphasize the central region. The real issue is which detector has the optimum sensitivity – which must be achieved by optimizing the efficiency and acceptance against the ability to reject rather large backgrounds.

To decide which geometry is best and what the final sensitivity is likely to be, one needs a systematic way to compare the physics reach of various detector geometries: central solenoidal type detectors (such as CDF, D0, CMS [10], and ATLAS [11]), forward collider detectors (such as LHC-B and COBEX) [7], a central dipole such as proposed for BCD [12] and which is under study by the EOI-2 group, and various combinations such as a solenoid with (a) forward dipole(s).

MCFAST gives us a tool to do these comparisons. It is fast so we can simulate and analyze enough background events to prove that the required, very large background rejections are achievable. It is flexible enough to handle the various geometries. It provides a reasonably accurate model of the tracking system so issues like acceptance, momentum and mass resolution, secondary vertex resolution, flavor tagging, and triggering can all be studied. Muon detection and electromagnetic calorimetry have been incorporated. Particle identification needs still to be included. The program is interfaced to most popular event generators. The geometry is specified using a simple ASCII file. Particles are traced through detectors and are smeared to account for resolution and multiple scattering. Decays in flight, γ conversions, and multiple interactions per crossing are all included. Tracking of charged particles is done using a Kalman filter technique.

4.1. Comparisons of central and forward detectors

We have been doing detailed studies of the sensitivity of a model central detector and a model forward detector for the decay $B^0 \to \pi^+\pi^-$.

The central detector covers a rapidity range $|\eta| < 1.5$. For this detector, the average (accepted) transverse B decay distance is $\approx$50 μm and the 3-dimensional decay distance is $\approx$1.3 mm. The vertex resolution for the two-pion decay mode is $\sigma_x = \sigma_y = 60$ μm and along the beam, $\sigma_z = 120$ μm.

The forward detector covers a rapidity range $1.5 < \eta < 4.5$. For this detector, the average (accepted) transverse B decay distance is $\approx$300 μm and the 3-dimensional decay distance is a few mm. The vertex resolution for the two-pion decay mode is $\sigma_x = \sigma_y = 7$ μm and along the beam direction, $\sigma_z = 90$ μm.

The goal of this particular simulation study is to provide a credible estimate of the sensitivity of the measurement of the CKM parameter $\sin 2\alpha$. The sensitivity is usually described by a formula like:

$$\delta(\sin 2\alpha) \propto \frac{1}{(\sqrt{\epsilon_{tag}} D_{mistag} D_{shape} D_{back} \sqrt{N_{\pi\pi \ reconstructed}}} . \qquad (1)$$

Here, $D_{mistag} = (1 - 2w)$, where w is the fraction of wrong sign tags from all sources including away-side mixing, charm cascade, decay in flight, and hadron punchthrough; D_{shape} comes from relating the measured asymmetry to the *amplitude* of the CP modulation. For this state, using a time-integrated analysis, $D_{shape} = 0.47$; and $D_{back} = \sqrt{\text{signal events/total events}}$ is the reduction in the "effective" number of signal events due to the presence of background.

For this analysis, after a $\pi^+\pi^-$ state in the vicinity of the B^0 mass which makes a good two track vertex is found, the background rejection is obtained by further use of vertex information. Sources of background include pairs of particles from the primary vertex which have the B invariant mass, particles from two different B or charm vertices with the right mass and which appear to verticize away from the primary vertex, particles from one B and the primary which have approximately the right mass and which appear to verticize away from the primary.

The requirements that one can use to reject these backgrounds and isolate a clean signal are:

– Vertex detachment: require L/σ_L, where L is the separation of the primary and candidate $\pi\pi$ vertex and σ_L is its uncertainty, to be greater than some cut, typically about 8. This requirement rejects most combinatoric background from the primary.

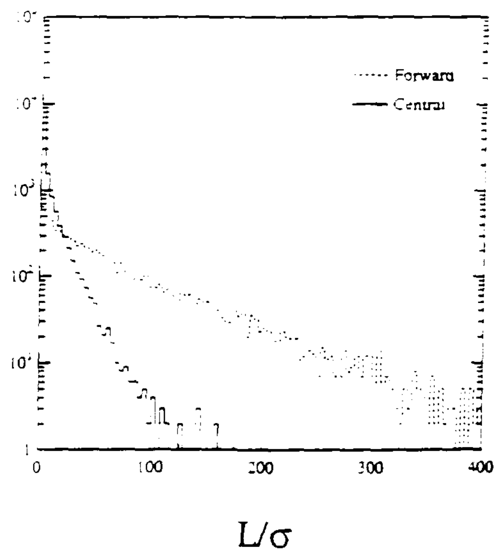

Fig. 2. L/σ_L for $B^0 \to \pi\pi$.

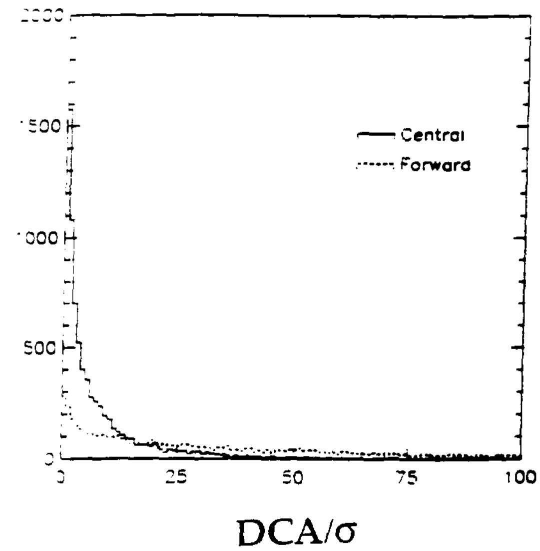

Fig. 4. Normalized pointback - DCA/σ of π from B^0 candidate to the primary vertex.

- B pointback: require the B reconstructed from the two pions to point back to the primary vertex within a few standard deviations of the pointback resolution. This provides excellent rejection power against particles coming from different B decay vertices.

- Daughters don't point back: require the two daughter pions to be inconsistent (individually) with the hypothesis that they came from the primary vertex (or perhaps even other secondary vertices) by at least a couple of standard deviations of the individual particle pointback resolution.

It has been found that the background is dominated by events that contain two B's where one track is chosen from each B. Since there are of order 10^5 times as many of these events as there are events that truly contain a $B^0 \to \pi^+\pi^-$, the requirements on background rejection are severe and each cut's efficiency and rejection must be carefully understood and included in the sensitivity calculation.

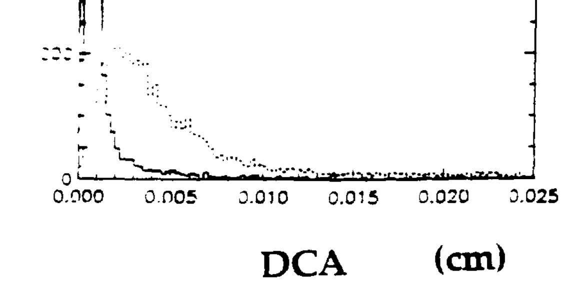

Fig. 3. Pointback - Distance of Closest Approach (DCA) of B^0 candidate to the primary vertex.

Fig. 2 shows the L/σ_L for the forward and central detector; Fig. 3 shows the pointback accuracy of the candidate B to the primary vertex; and Fig. 4 shows the pointback accuracy for the daughter particles with respect to the primary vertex.

We have used MCFAST to carry out a preliminary sensitivity analysis for $\sin 2\alpha$ using a Monte Carlo sample of 40 000 "signal" events generated with a B^0 decaying to $\pi^-\pi^-$ and 300 000 "background" events each with two B's decaying to all decay modes with our best knowledge of the branching fractions.

Fig. 5 shows the signal and background for accepted and reconstructed events for the forward detector. Recall that, in all the histograms for the background, the bin populations need to be multiplied by 10^4 to correct the generated samples to the real-world ratio of the signal and background events. Fig. 6 shows the same plot for the central detector. Finally, Figs. 7 and 8 show the effect of all the cuts, including the pointback and non-pointback cuts described above.

The following observations are in order:

- The central geometry starts off with a higher total yield when only acceptance is considered. At this point, background would totally swamp the signal;

- As cuts are piled on to reduce the background, the central geometry loses events more rapidly until, when all the cuts are applied, the event yield is more than twice as large for the forward geometry;

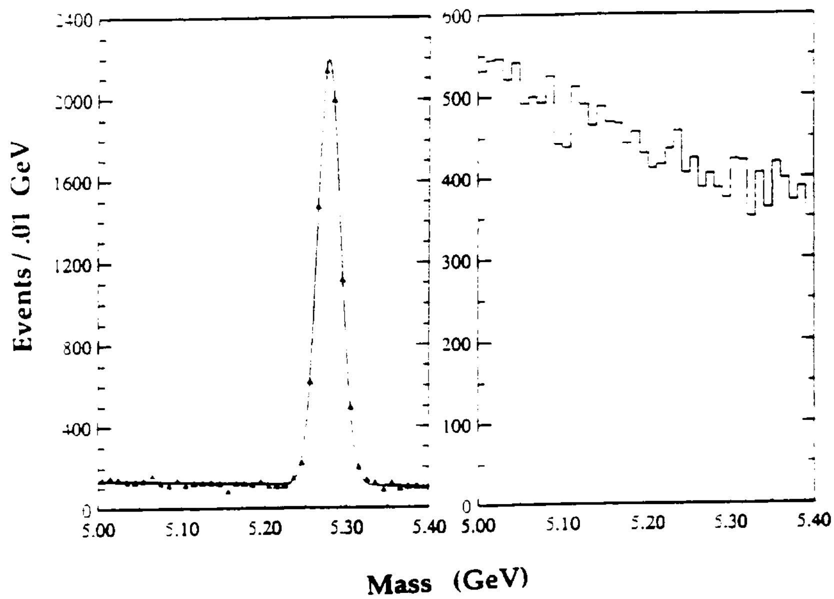

Fig. 5. *Forward detector:* $\pi^-\pi^-$ invariant mass distribution reconstructed *without* vertex cuts: (left) 40000 event sample where each event contains a $B^0 \to \pi\pi$ combination; (right) 300000 event sample of generic $b\bar{b}$ decays.

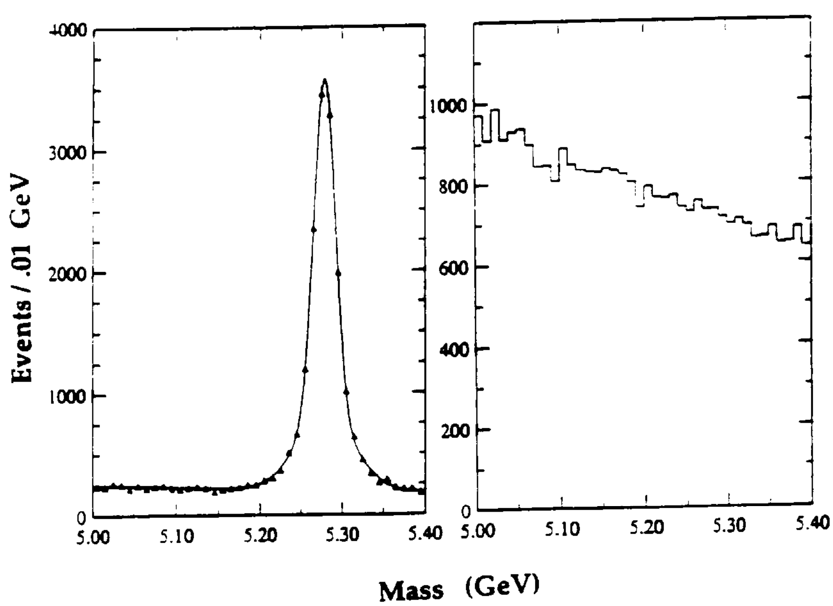

Fig. 6. *Central detector:* $\pi^-\pi^-$ invariant mass reconstructed *without* vertex cuts: (left) 40000 event sample where each event contains a $B^0 \to \pi\pi$ combination; (right) 300000 event sample of generic $b\bar{b}$ decays.

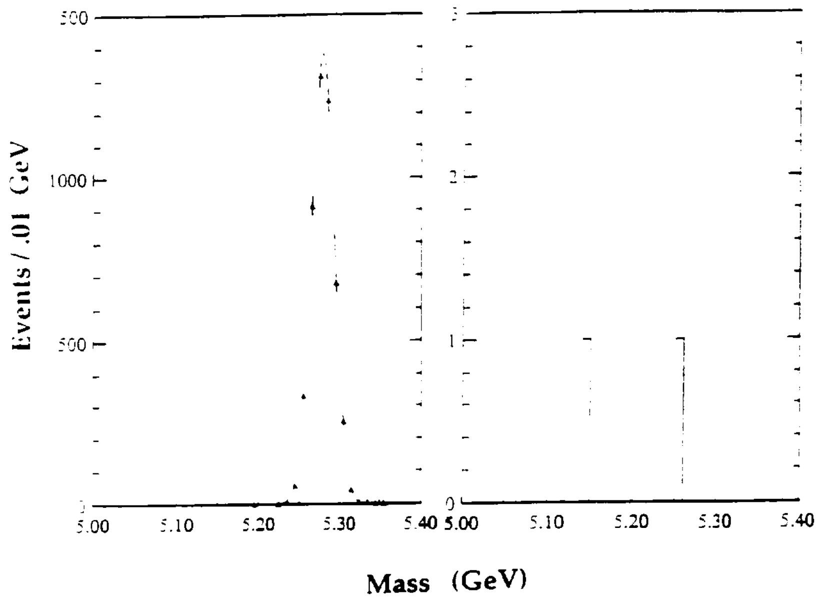

Fig. 7. *Forward detector:* $\pi^-\pi^-$ invariant mass reconstructed *with all* vertex cuts: (left) 40000 event sample where each event contains a $B^0 \to \pi\pi$ combination; (right) 300000 event sample of generic $b\bar{b}$ decays.

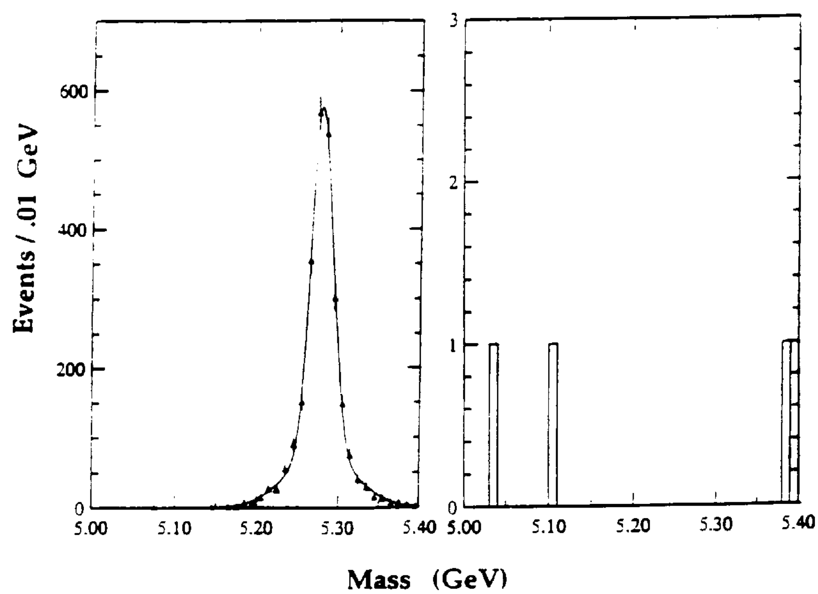

Fig. 8. *Central detector:* $\pi^-\pi^-$ invariant mass reconstructed *with all* vertex cuts: (left) 40000 event sample where each event contains a $B^0 \to \pi\pi$ combination; (right) 300000 event sample of generic $b\bar{b}$ decays.

– In many cases, the sensitivity to small changes in the cuts is greater for the central detector so it is expected that the predictions for the central geometry are less robust against "cut optimism" than for the forward geometry;

– Detailed investigation shows that the role of multiple scattering is crucial in understanding differences in the efficiencies and rejections of the vertex cuts;

– While the plots of the background look clean when all cuts are applied, one needs to remember that the bin populations need to be multiplied by 10^4. It is clear that the statistics on the background are too low; we are therefore generating a much larger sample of background events to correct this. It is already clear that these cuts result in a signal-to-background roughly of 1 : 1. This definitely needs to be taken into account in estimating the sensitivity to $\sin 2\alpha$.

– The analysis shown here is not complete. It neglects particle identification which is needed to remove the decays $B^0 \to K^-\pi^-$ and $B_s \to K^-K^-$ from the signal. It also completely neglects triggering and it neglects flavor tagging, which is necessary for the observation of CP violation in this state. A preliminary study of tagging using away-side muons, one of several tagging strategies, indicates a further loss of sensitivity of the central detector with respect to the forward detector.

A very preliminary attempt to calculate the sensitivity to $\sin 2\alpha$ using a muon tag only and unoptimized cuts gives a result of 0.17 for the uncertainty in $\sin 2\alpha$ for the forward geometry with one year of running at a luminosity of 10^{32}. A signal-to-background of 1 : 1 is used. The effect of wrong-sign muon tags are included. We expect other tagging strategies to improve the uncertainty to less than 0.1 per year. We have also begun to simulate a "dipole" geometry which has a factor of two better acceptance and is expected to improve the result to 0.05–0.07 per year.

5. Future plans

The study is now being extended to other states, such as $B^0 \to \psi K_s$ and DK states. The study will refine and conclude its initial survey of geometries in the next year. Major areas of investigation will be triggering, tagging strategies, and particle identification. We will, as part of the task, calculate the sensitivity of the upgraded CDF and D0 and of LHC-B. If the outcome of the study shows that a competitive second generation experiment can be carried out at the Tevatron, the group will seek Fermilab's encouragement to submit a letter of intent.

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References

[1] A. Eisner et al., SLAC Publication *SLAC-PUB-353 (1989)*;
SLAC BABAR Collaboration: Technical Design Report (1995);
G. Wormser, Nucl Instr. and Meth. A 351 (1994) 54;
P. Harrison, these Proceedings (3rd Int. Workshop on B-Physics at Hadron Machines, Oxford, UK, 1995) Nucl. Instr. and Meth. A •••

[2] Y. Sakai, Nucl. Instr. and Meth. A 333 (1993) 42;
J. Haba, these Proceedings (3rd Int. Workshop on B-Physics at Hadron Machines, Oxford, UK, 1995) Nucl. Instr. and Meth. A ••• ;
BELLE Collaboration, Letter of Intent (1994).

[3] CLEO III Detector: Design and Physics Goals, CLEO preprint CLNS 94/1277 (1994);
S.W. Gray, Nucl. Instr. and Meth. A 351 (1994) 43;
S. Stone, these Proceedings (3rd Int. Workshop on B-Physics at Hadron Machines, Oxford, UK, 1995) Nucl. Instr. and Meth. A •••

[4] HERA-B, An Experiment to Study CP Violation in the B System Using an Internal Target at the HERA Proton Ring, DESY-PRC 94/02 (May 1994);
W. Hofmann, Nucl. Instr. and Meth. A 333 (1993) 153;
P. Krizan et al., Nucl. Instr. and Meth. A 351 (1994) 111.

[5] CDF Collaboration, *Expression of Interest in a Future Collider Detector at B0.*

[6] D0 Collaboration, Expression of Interest Based on the D0 Detector for Run 3 at the Fermilab Tevatron.

[7] LHC-B Letter-of-Intent, A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation, CERN/LHCC 95-5 (25 August 1995);
J. Ellett et al., A Dedicated Beauty Experiment for the Tevatron Collider, Fermilab Proposal Number 845 (January 1991);
See also S. Erhan, these Proceedings (3rd Int. Workshop on B-Physics at Hadron Machines, Oxford, UK, 1995) Nucl. Instr. and Meth. A •••

[8] R. Edelstein et al., Expression of Interest for a Dedicated Hadron Collider B Experiment at the Fermilab Tevatron.

[9] A.S. Boehnlein, MCFAST, A Parameterized Fast Monte Carlo For Detector Studies, contributed paper to CHEP95.

[10] CMS Technical Proposal, CERN/LHCC 94-38, LHCC/P1 (15 December 1994).

[11] ATLAS Technical Proposal, CERN/LHCC 94-43, LHCC/P2 (15 December 1994).

[12] Bottom Collider Detector, Expression of Interest to the SSC (May 1990).